Were Mass Extinctions Fast or Slow?

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Introduction

- **What is a mass extinction?**
  - A mass extinction event is characterised by a significant depletion of known species within a specific timeframe (Scoville, 2017), marked by extinction rates notably higher than the typical background extinction rates observed over geological time scales (Stigall, 2010).
- **What do we define as fast and slow?**
  - Rapid mass extinction events are distinguished by their relatively short duration, typically occurring within approximately 100,000 years, leading to a substantial loss of species within a compressed time frame (Molina, 2014).
  - Slow mass extinction events, on the other hand, are characterised by their prolonged duration, spanning around 1 million years, and in some cases extending over several million years, resulting in a gradual but significant decline in biodiversity over an extended period (Molina, 2014).
  - These definitions are contentious, and appear to be a key cause of the disagreement within this debate - and so establishing these timescales at the start of our argument is essential.
- **Why is this important?**
  - Shapes evolution: Mass extinctions influence the course of evolution by determining which species survive and which perish, thereby shaping the characteristics and diversity of future life forms.
  - Insight into catastrophes: Studying mass extinctions offers valuable insights into the effects of extreme catastrophes on biodiversity, helping us understand the resilience of ecosystems and species to such events.
  - Understanding the sixth mass extinction: The ongoing extinction event is crucial to comprehend as it represents a significant driver of macroevolutionary change in the current biosphere. However, the complex interplay between environmental disruptions caused directly and indirectly by human activity and biological responses remains inadequately understood.

Mass extinctions exhibit a predominantly fast tempo, with durations typically ranging from 100,000 to 1 million years. Despite uncertainties in the fossil and stratigraphic record, the overwhelming evidence suggests that these events have swift and profound impacts on the global biosphere, emphasising the urgent need for further research to better understand patterns of recovery and the distribution of continental fossils in the stratigraphic record.

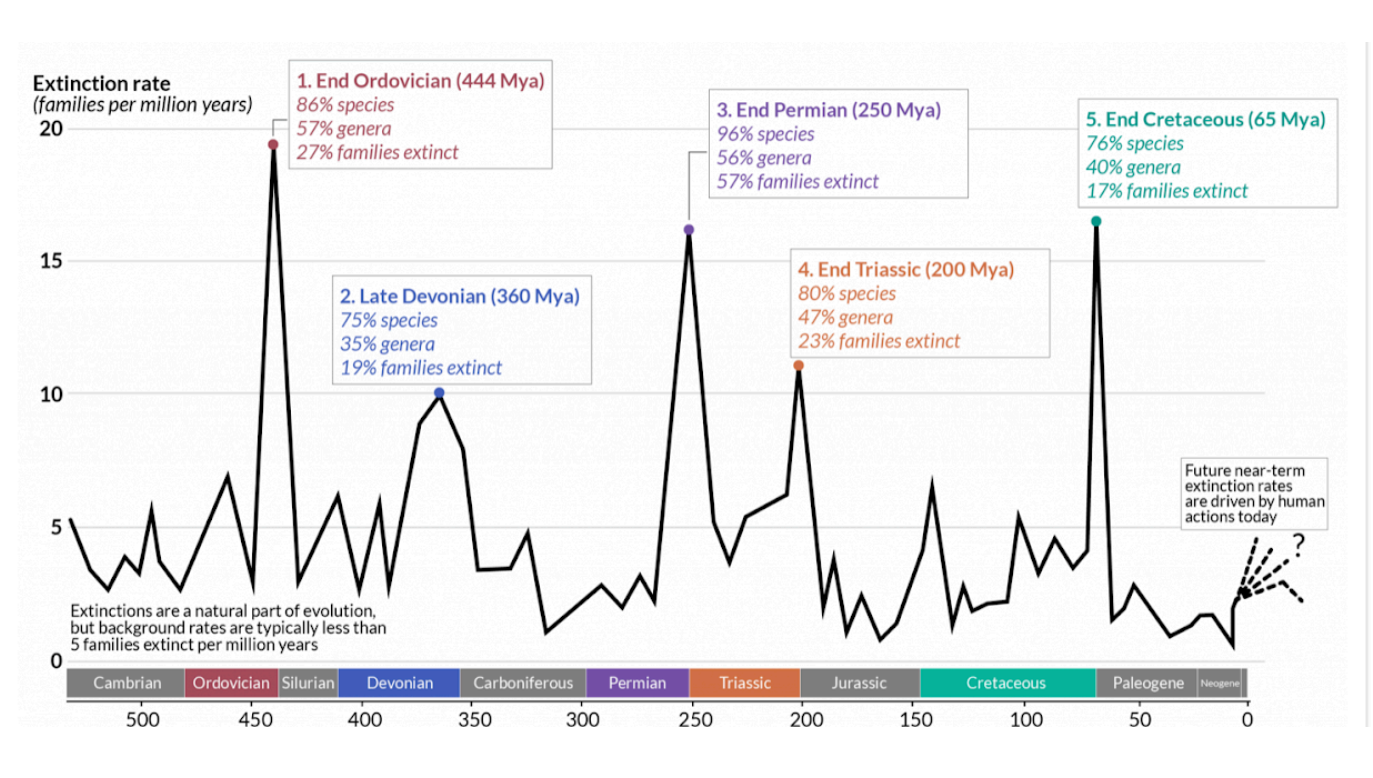

Figure 1 - Extinction rates over time for the 5 main mass extinction events (Ritchie, 2022). The five major extinction events are highlighted, demonstrating the increased rate required for a mass extinction to be classified.

Mass Extinctions – Scientific Context

- Earth's 4.6-billion-year history is marked by five major mass extinctions, including the End-Ordovician, Late-Devonian, End-Permian, End-Triassic, and End-Cretaceous events, as seen in Figure 1.
- Each mass extinction event varied in magnitude, rate and underlying causes, resulting in significant biodiversity loss and creating opportunities for rapid speciation and evolutionary adaptation among surviving species (Scoville, 2017).
- Fluctuations in Carbon-13/Carbon-12 ratios in both organic and inorganic materials are commonly linked to extinction events and environmental catastrophes (Hesselbo et al. 2002), and can be used as evidence to support environmental causes of events.
- Interpretations of the tempo of mass extinctions and recoveries hinge on the distribution of fossils in the stratigraphic column (Holland, 2020), which as a form of evidence is inherently uncertain.
- It's crucial to acknowledge that the first and last occurrences of species in the fossil record don't necessarily represent the times of extinction and origination. Face-value interpretation of the stratigraphic record can lead to erroneous conclusions about the timing and duration of extinction events, as well as the pace of recovery (Holland, 2020).

Fast Mass Extinctions

The End-Permian, End-Triassic, & End-Cretaceous Mass Extinctions all fit the definition of 'fast extinctions'. They are generally characterised by a single major pulse.

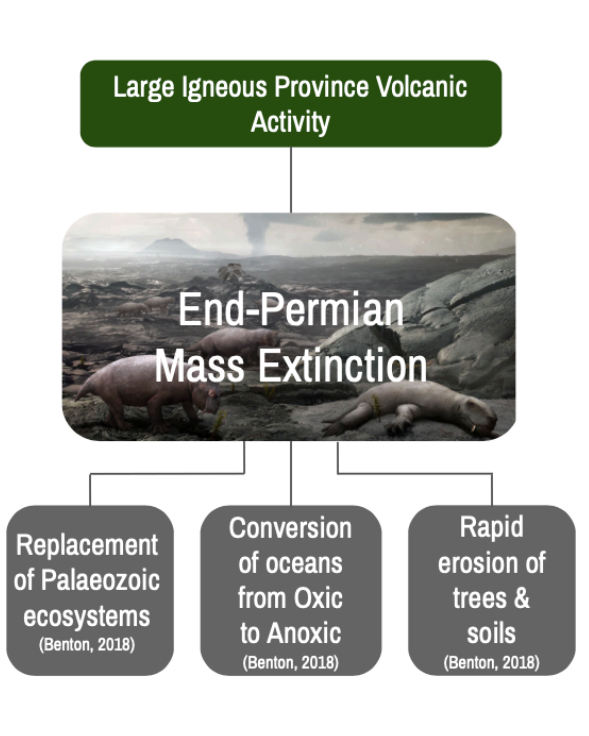
Large Igneous Province Volcanic Activity
End-Permian Mass Extinction
Replacement of Palaeozoic ecosystems
(Benton, 2018)
Conversion of oceans from Oxic to Anoxic
(Benton, 2018)
Rapid erosion of trees & soils
(Benton, 2018)

Figure 2 - End-Permian Mass Extinction flowchart. Grey boxes represent forms of evidence for each event, and dark green boxes represent causes.

The End-Permian Mass Extinction

Background: The End-Permian involved the extinction of ≈96% of all known species over ≈60Kyr c.250Ma (Scoville, 2017; Burgess *et al*., 2014).

Evidence (Benton, 2018) (Figure 2):

These forms of evidence suggest a timeframe for the event via durations in their respective records.

- Fossil record: the rapid replacement of Palaeozoic ecosystems (Rugose and Tabulate coral, crinoid, and brachiopod dominated) with Mesozoic ones (Scleractinian coral, mollusc, and malacostracan arthropod dominated).
- Marine sedimentary record: the sudden change from oxic to anoxic conditions, shown by decreases in δ18O in shallow marine biogenic carbonate.
- Terrestrial sedimentary record: the sudden prescence of coarse grained sediments from rapid erosion of trees and oils, indicating a hiatus from soil production.

Cause: Global temperatures increasing to reach ≈35-40°C, resulting from volcanic activity at Large Igneous Provinces (Siberian and Emeishan Traps and the Wrangellia Basalts) in a single major pulse bookended by smaller pulses (Benton, 2018; Holland, 2019). While this period of volcanism was more protracted, evidence suggests that a tipping point was reached which triggered the mass extinction event.

The 60kyr timeframe, estimated using the Oxygen isotope record, makes this a fast extinction (Burgess *et al*., 2014).

The End-Triassic Mass Extinction

Background: The End-Triassic involved the extinction of over 50% of all known species over ≈60kyr c.200Ma (Scoville, 2017).

Evidence: (Hesselbo *et al*., 2002; Scoville, 2017) (Figure 3)

These forms of evidence suggest a timeframe for the event via durations in their respective records.

- Fossil record: the sudden dominance of dinousaurs in the biostratigraphic record during the recovery period, a result of their rapid radiation to fill niches left empty by the extinction.
- Isotope record: the sudden, short-lived negative excursion in Carbon values resulting from volcanic outgassing demonstrates the rapid onset of environmental change.

Cause: Flood Basalts and related volcanic activity, with a few smaller extinction events of the same cause also associated over the surrounding 18Myr (Hesselbo *et al*., 2002; Scoville, 2017). Again, it is likely that the extinction was triggered by an environmental tipping point.

The 60kyr timeframe, estimated using isotopic and palaentological data, makes this a fast extinction (Hesselbo *et al.*, 2002).

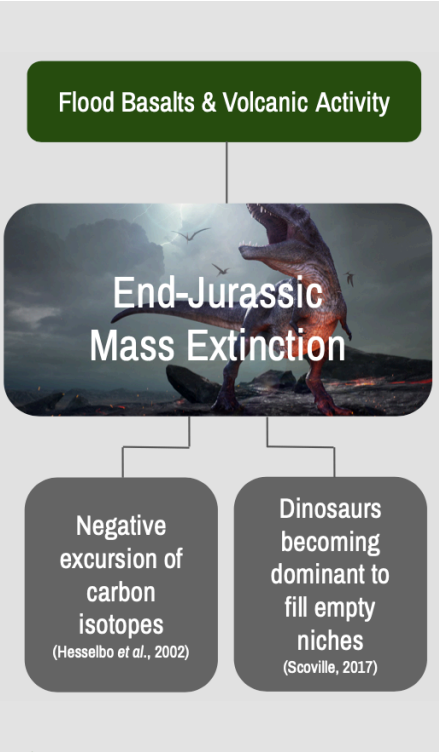
Flood Basalts & Volcanic Activity
End-Jurassic Mass Extinction
Negative excursion of carbon isotopes
(Hesselbo et al., 2002)
Dinosaurs becoming dominant to fill empty niches
(Scoville, 2017)

Figure 3 - Jurassic-Triassic Mass Extinction flowchart. Grey boxes represent forms of evidence for each event, and dark green boxes represent causes.

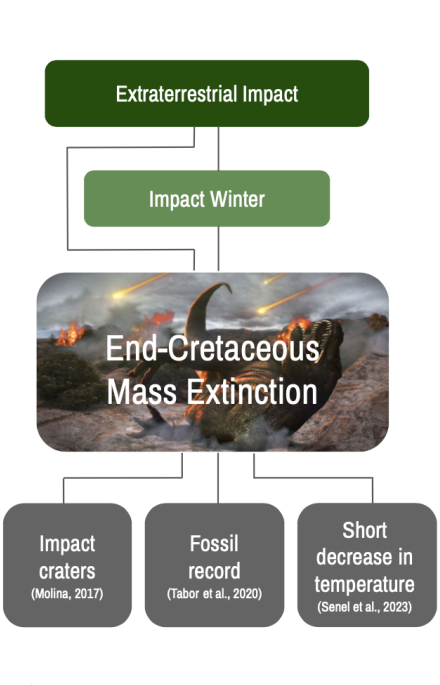

Figure 4 - Cretaceous-Palaeogene Mass Extinction flowchart. Grey boxes represent forms of evidence for each event, and dark green boxes represent causes.

The End-Cretaceous Mass Extinction

Background: The End-Cretaceous involved the extinction of the dinosaurs and ≈75% of all species over ≈20yr c.65Ma (Scoville, 2017).

Evidence:

These forms of evidence suggest a timeframe for the event via durations in their respective records.

- Fossil record: the death of the dinosaurs, and sudden mass accumulation of fossils in a short-lived stratigraphic layer.
- Geological record: impact craters, implying rapid change
- Iridium spike at Cretaceous-Palaeogene boundary - geochemical evidence for the asteriod impact and its timing (Holland, 2020).
- Proxy climate record: the drop in temperature lasting ≈15 years in a period known as 'impact winter'.

Cause: Extraterrestrial impact of an asteroid or meteor and the resulting 'impact winter', a period of low light and cold temperatures caused by the addition of new materials to the atmosphere such as sulphur and dust from the explosions (Molina, 2015).

The 20yr timeframe suggested by atmospheric composition records, consisting of impact and subsequent effects, makes this a fast extinction (Senel *et al.,* 2023).

Were there any slow mass extinctions?

Do the End-Ordovician and Late-Devonian Mass Extinctions, both two-pulse events, fit the criteria of a 'slow mass extinction'?

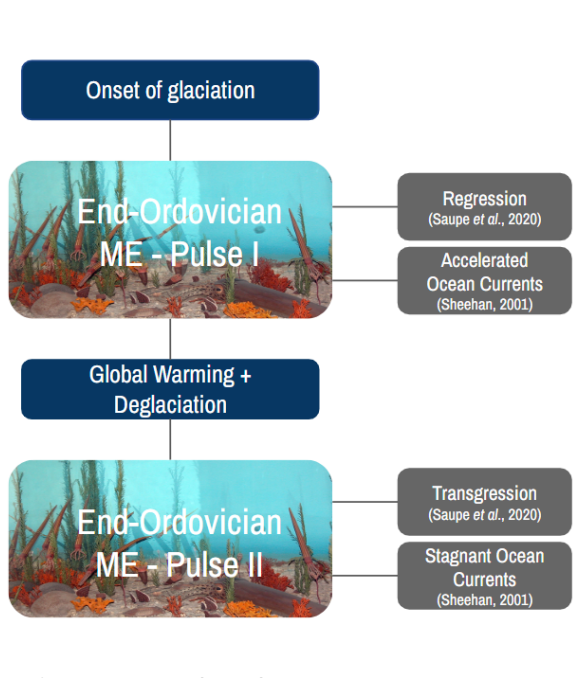

Figure 5 - End-Ordovician Mass Extinction flowchart. Dark blue boxes represent main causes and grey boxes represent secondary effects.

The End-Ordovician Mass Extinction

Background: The End-Ordovician extinction led to the extinction of 85% of all species across the Hirnantian stage, lasting 1.4 million years (Sheehan, 2001).

Evidence:

These forms of evidence suggest a timeframe for the event via durations in their respective records.

- Fossil Record: reduction of brachiopod and bryozoan families (Sheehan, 2001).
- Biostratigraphy: dating of important fossil groups such as conodonts (Delabroye and Vecoli, 2009).
- Chemostratigraphy: positive isotope excursion (Delabroye and Vecoli, 2009).

Cause: The extinction event was characterised by two pulses (Saupe *et al*., 2020) following two distinct events (see Figure 5):

1. Glaciation over Gondwana (which lay over the South pole) at the beginning of the Hirnantian leading to regression and accelerated ocean currents (Saupe *et al*., 2020).
2. Deglaciation and global warming at the end of the stage leading to transgression and stagnation of ocean currents (Saupe *et al*., 2020).

Was the End-Ordovician really 'slow'?:

- Zircon-dating of bentonite beds in China found that the Hirnantian stage of the Ordovician was only 0.47 million years (Ling *et al*., 2019). If so, this extinction was in excess of 1 million years faster than originally thought, and fits with the definition of 'fast' outlined previously.
- While this extinction is slower than those previously identified as fast, the multi-phase nature of this extinction indicates that each pulse would have been individually even faster.

The Late-Devonian Mass Extinction

Background: The Late-Devonian extinction involved the extinction of up to 80% of all species over 25 million years (Fan *et al*., 2020), the slowest of the 'Big 5' mass extinctions.

Evidence:

These forms of evidence suggest a timeframe for the event via durations in their respective records.

- Fossil Record: replacement of calcite reef builders with siliceous organisms (Becker *et al*., 2020).
- Stratigraphy: onset of anoxic and transgressive facies such as shales (Aretz and Corradini, 2021).

Cause: The event also followed a two-pulse extinction pattern (Scoville, 2017) - see Figure 6.

1. Colonisation of the land by plants leading to ocean anoxia (Becker *et al*., 2020).
2. Global warming associated with possible volcanism (Becker *et al*., 2020).

Does the late-Devonian fit the criteria of a mass extinction?:

- Late-Devonian extinction rates are not significantly higher than extinction rates during background intervals (Stigall, 2010) (see Figure 1)
- Reduction in speciation rate rather than an increase in extinction rate (Stigall, 2010). No new species were adapting to fill ecological niches lost from continuining extinction, potentially due to the spread of invasive species.
- Should it rather be called a 'biodiversity crisis' or 'diversity decline' (Stigall, 2010; Fan *et al*., 2020)?

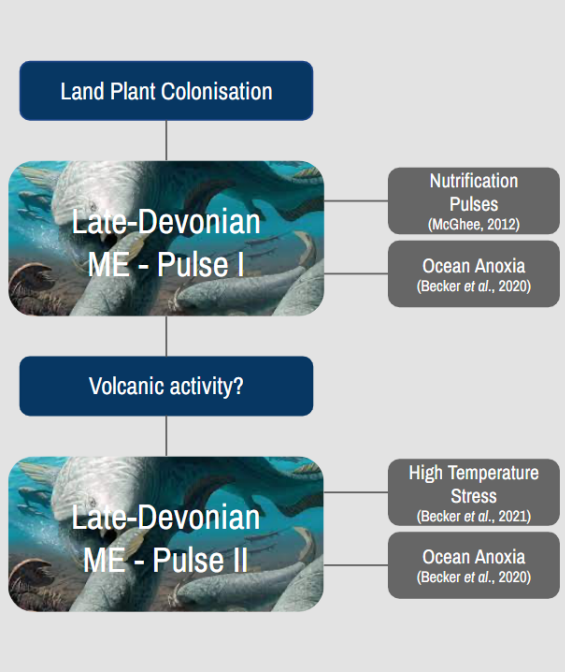

Figure 6 - Late-Devonian Mass Extinction flowchart. Dark blue boxes represent main causes and grey boxes represent secondary effects.

Why are mass extinctions fast? – Discussion

Press Extinctions, in which extinction and recovery overlap and are of sufficient duration for adaptive responses to reduce the scale of extinction. This type of extinction is more common in the entire record (Holland, 2020), and better understood as periods of accelerated biotic overturn coinciding with long-term environmental change. The Late-Devonian could be considered an example of a (large-scale) press extinction.

Pulse Mass Extinctions have fast onsets and do not allow for adaptations to emerge. They appear to be caused by catastrophic volcanism or impact events, and resulting vastly elevated extinction rates lead to global ecological overturn. The end-Permian Mass Extinction is the largest magnitude example of a pulse extinction.

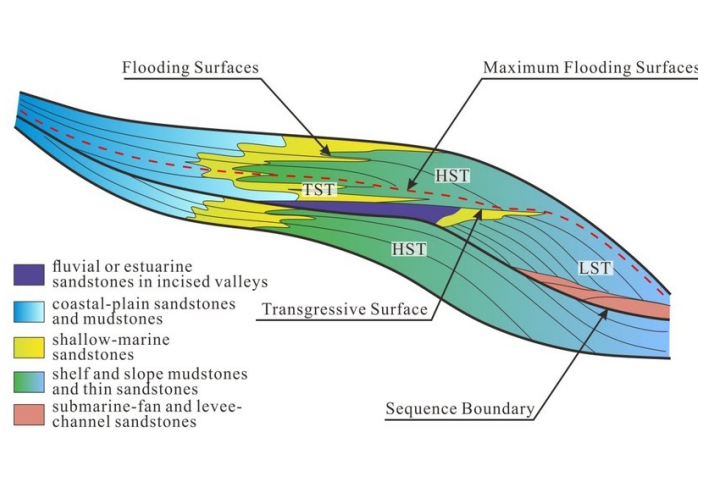
Flooding Surfaces
Maximum Flooding Surfaces
HST
TST
HST
LST
Transgressive Surface
Sequence Boundary
fluvial or estuarine sandstones in incised valleys
coastal-plain sandstones and mudstones
shallow-marine sandstones
shelf and slope mudstones and thin sandstones
submarine-fan and levee-channel sandstones

Figure 7 - sequence stratigraphic features associated with LAD and FAD clusters (Lin *et al*., 2017). LADs tend to be associated with flooding surfaces, subaerial unconformities and surfaces of forced regression, while FADs are associated with shallowing upwards sequences during HST periods.

Sequence Stratigraphy and Fossil Record Uncertainty

- First Occurence Datum (FAD) and Last Occurence Datum (LAD) do not represent the time of origination or extinction of a species.
- Clusters of LADs followed by FADs are widely interpreted as mass extinctions followed by recovery, but this can be altered by sea level and sedimentation rates.
- But LADs and FADs might not be found in their original position in the stratigraphic records, are are instead often associated with sequence stratigraphic features (Figure 7).
- The stratigraphic record needs to be studied alongside the fossil record in order to account for the uncertainty in both.

Even when uncertainty is accounted for, pulse mass extinctions appear to be caused by large scale, rapid onset events which lead to a rapid response in the biosphere, as evidenced by the large scale volcanism and environmental change that caused the end-Permian mass extinction. Mass extinctions appear anomalous in the fossil record, but their causes are also truly anomalous in the stratigraphic record, and take near immediate effect on the biosphere.

There are some extinction events that at face-value appear slow, but new radiometric dating suggests that the end-Ordovician mass extinction was much faster than previously thought and may have fallen victim to misinterpretation of the fossil and stratigraphic record - theories now suggest this was a fast mass extinction by our classification. The late-Devonian extinction event appears to be a press extinction, rather than a rapid pulse event, and there is debate around whether the extinction rate was significantly above the background enough to be classified as a mass extinction at all - and so while this is definitely a slow event, it might not be applicable when studying large-scale *mass* extinctions.

The end-Permian and end-Triassic mass extinctions are both classic examples of fast pulse extinctions caused by large-scale volcanism, while the end-Cretaceous mass extiction occured over an even shorter time period. These events were catastrophic environmentally and ecologically, leading to fast extinction and a protracted recovery period.

Distinguishing between mass extinctions and smaller events with elevated extinction rates is key when determining the rate of mass extinction, as smaller events do happen over longer periods of time and if incorporated into timescale interpretations could misleadingly sway the results. However, when all (uncontested) mass extinctions are studied the trend is that they are fast, generally as a result of their catastrophic triggers.

Conclusions

- Mass extinctions are fast, having durations in the range of 100kyr to 1Myr. These events have intense and rapid impacts on the global biosphere.
- There is unavoidable uncertainty in the fossil and stratigraphic record, but when combined accurate conclusions about the tempo and pace of mass extinctions can be drawn.
- Further study should focus on patterns of recovery and the distribution of continental fossils in the stratigraphic record, both of which are currently poorly understood, and would add new layers of evidence to this debate.
- These conclusions are vital for understanding the trajectory of the current extinction event experienced in the modern biosphere, potentially highlighting its gravity.

Suggestions for Further Reading

- Paleogene Extinction Events: speed and intensity of the four extinction events during the Paleogene (63Ma to 23Ma).
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- The sixth mass extinction - fast?
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  - Spalding, C. and Hull, P.M. (2021). Towards quantifying the mass extinction debt of the Anthropocene. *Proceedings of the Royal Society B: Biological Sciences*, 288(1949). doi:https://doi.org/10.1098/rspb.2020.2332.

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